ORIGINAL ARTICLE

Natural Features Technique for Non-Contact Three Dimensional Craniofacial Anthropometry Using Stereophotogrammetry

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ABSTRACT
This paper describes the use of stereophotogrammetry approach to measure and hence identify accurately three-dimensional (3D) coordinates of important landmarks on a craniofacial surface. A “novel” technique dubbed as “natural features” technique was employed to accurately compute the 3D coordinates of selected craniofacial landmarks. The natural features technique involves the use of 3D coordinates of the natural features (such as acne, scar, corners of eyes, edge of mouth, point of chin, etc.) that appear on the craniofacial surface as an absolute stereophotogrammetric mapping control points. The 3D coordinates of the natural features were gained using digital photogrammetric bundle adjustment method. Validation of the proposed technique has firstly been carried out using mannequin and finally, it was applied on the real-life human faces. The result shows that the craniofacial landmark measurement accuracy of 0.8mm with one standard deviation can be successfully achieved by the proposed technique.

Key words: stereophotogrammetry, craniofacial landmarks, 3D coordinates

INTRODUCTION

Craniofacial anthropometric measurements required high quality measuring tools in order to get the highest possible measurement accuracy (Farkas *et al.*, 1996). Among the methods used, stereophotogrammetry was promised to be familiar as a non-contact, non-invasive, reproducible, fast, high-accuracy, practical and cost-effective for measurement of facial morphology (Naftel *et al.*, 2004; Burke *et al.*, 1983; Hay *et al.*, 1985; Majid *et al.*, 2005; Meintjes *et al.*, 2002; Ras *et al.*, 1995; Wagner *et al.*, 2005; Johnston *et al.*, 2003).

Generally, photogrammetric control frame with targets (generally known as control frame technique) is required for the stereo orientation of the craniofacial stereo-photographs. The control is needed to allow scaling and orientation of the spatial model during the later analysis (Newton, 1974). The control frame may be placed over the patient’s head (Savara and George, 1984); near both side of the head (Peterson, 1993) and in Schewe and Ifert (2000) the control frame were placed on a helmet. These three designs almost certainly covered in all published photogrammetric control configurations (Majid *et al.*, 2005). However, tests show that the recommended location of the targets on the control frame was not suitable for high accuracy stereo-orientation. The accuracy in the Z (along the optical axis) does not satisfy the project requirement of 0.7 mm. It becomes clear that the targets are too far from the facial surface. The problem can be solved by using natural features technique which involved the used of natural features such birth mark, acne or scar as photogrammetric control for the stereo orientation of the craniofacial stereo-photographs. In certain cases, the natural features may be tattooed on the object for the duration of the investigation (Newton, 1974).

A method was developed to obtain high accuracy 3D coordinate of the natural features. It involves a photogrammetric bundle adjustment of photographs from the three stereo-cameras using the photogrammetric control frame targets. The photogrammetric bundle adjustment computes the 3D coordinate of the natural features. Subsequently, the 3D coordinates of the natural features are used to carry out absolute orientation process of the craniofacial stereo-models.

MATERIALS AND METHODS

Setup of stereophotogrammetric system

The design of the photography is based on three stereo-pairs of photograph. Six Sony CyberShot F828 digital cameras were set up 600 mm from the object to capture the stereo images. The cameras were electronically synchronized using a LANC Shepherd controller (Figure 1).

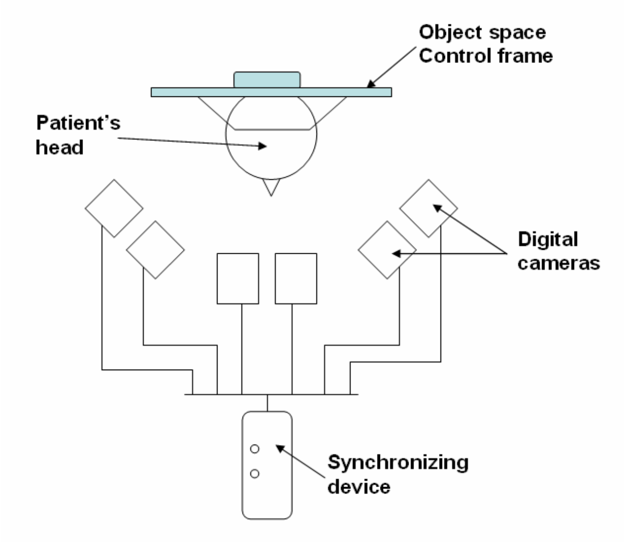

Figure 1 Stereo-photographic system used in the study

Individual camera was calibrated independently using a three-dimensional calibration device (Chong and Scarfe, 2000; Majid et al., 2005). The device consists of a camera mount and a three-dimensional (3D) test field. Retro-targets are placed in row and column as shown in Figure 2.

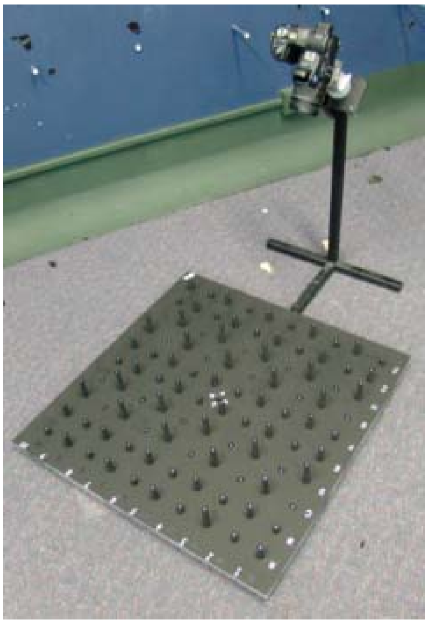

Figure 2 Three-dimensional camera calibration device

A photogrammetric control frame was built to provide an accurate 3D control for the research (Figure 3). Retro-targets were used to highlight the control points. The photogrammetric control frame also requires accurate calibration. The x, y and z coordinates of the targets were determined using convergent photographs and a bundle adjustment (Chong and Strafford, 2002). The coordinates would be used for the absolute orientation of the stereo models and for computing natural features 3D coordinates.

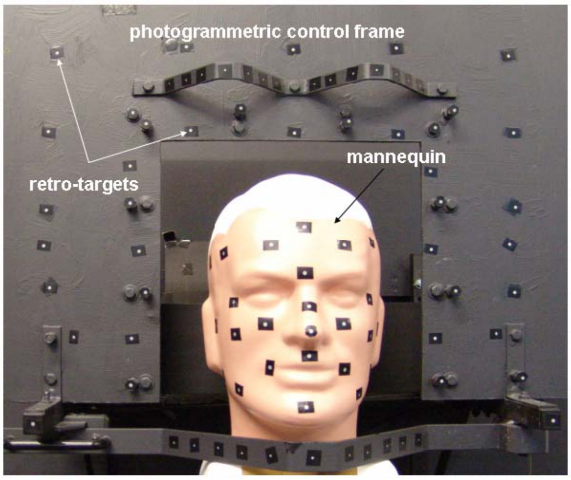

Figure 3 The photogrammetric control frame

Data collection

The data collection involved with photography process of the test objects. Two test objects involved in the research, the mannequin with retro-targets to represent the simulated natural features and real-life human faces. The photography process consists of four stages: (a) a convergent photography of the mannequin to capture a set of convergent photographs for the determination of 3D coordinates of the simulated natural features, (b) a stereo photography to capture a set of stereo-photographs of the mannequin for stereo-digitizing of the simulated natural features (c) a stereo photography to capture a set of stereo-photographs of real-life human faces with retro-targets and (d) a stereo photography to capture a set of stereo-photographs of real-life human faces without retro-targets. Stage (a) which involved with the used of a digital camera, can only be applied to the mannequin since this test object is rigid and does not having a movement effect like real-life human faces.

Standard digital caliper with the accuracy of 0.1mm was used to measure the linear distances between the selected natural features both on the mannequin and real-life human face with retro-targets. The caliper was calibrated where the value of zero was always started at the accurate scaling designed on the caliper. Each distance was measured three times and the average of the distances was calculated.

Data processing

As general, the data processing part consists of three stages, (a) photogrammetric bundle adjustment process for the determination of the 3D coordinates of simulated and real natural features, both on the mannequin and real-life human faces, respectively, (b) photogrammetric stereo orientation process which includes interior, relative and absolute orientation of stereo images and (c) photogrammetric stereo digitizing to digitize the selected craniofacial landmarks (using Vectorization module in DVP software).

In this study, the three sets of captured stereo images were processed separately. Each stereo image also involved with two different three-dimensional stereophotogrammetric mapping controls for absolute orientation; (a) by using signalized targets established on the photogrammetric control frame (known as control frame technique) and (b) by using the coordinates of the natural features on the craniofacial surface (known as natural features technique). For each process, the three-dimensional coordinates of the selected natural features were measured three times stereoscopically and the average of the coordinates was calculated. Figure 4 shows the process of measuring and digitizing craniofacial landmarks using DVP software.

Figure 4 Stereo digitizing using Digital Video Plotter (DVP) Photogrammetric Workstation.

RESULTS

The results consist of (a) the photogrammetric bundle adjustment 3D coordinate of the simulated natural features on the mannequin and natural features on the real-life human faces, (b) the 3D coordinates of simulated and real-life natural features from stereo digitizing via stereo images both from control frame technique and natural features technique, respectively. For data analysis, several simulated and real-life natural features on the mannequin and real-life human faces were selected as test points. Figure 5 and Table 1 shows the 3D coordinates of the test points on the mannequin, while Figure 6 and Table 2 shows the 3D coordinates of the test points on real-life human face

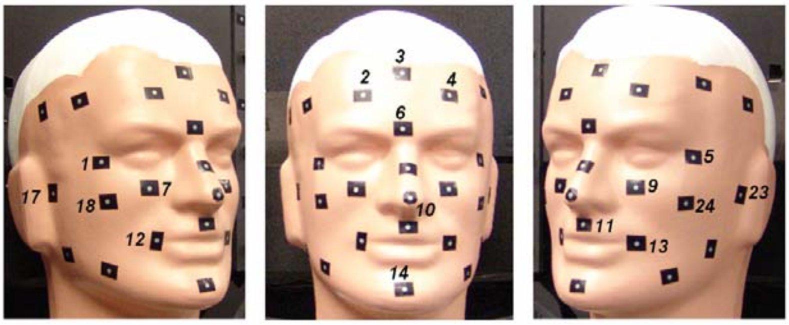

Figure 5 Selected test points (simulated natural features) on the mannequin

Figure 6 Selected test points (natural features) on the real-life human face

Table 1 3D coordinates of selected simulated natural features (test points) on the mannequin

ID	X (Bundle) (mm)	Y (Bundle) (mm)	Z (Bundle) (mm)	X (Natural Features) (mm)	Y (Natural Features) (mm)	Z (Natural Features) (mm)	X (Control Frame) (mm)	Y (Control Frame) (mm)	Z (Control Frame) (mm)
1	2511.989	970.216	79.364	2512.094	970.441	79.214	2508.227	970.135	83.696
2	2544.416	1017.719	101.152	2544.251	1017.747	103.030	2544.237	1019.448	92.477
3	2572.911	1033.141	98.123	2572.731	1033.129	99.636	2573.522	1035.283	89.164
4	2605.876	1016.298	100.410	2605.731	1016.444	100.140	2607.379	1018.057	90.253
5	2632.129	969.580	72.155	2632.939	969.557	73.763	2636.107	969.235	77.782
6	2570.732	992.318	111.301	2570.683	992.377	111.569	2571.523	993.595	100.341
7	2537.597	950.340	100.601	2537.463	950.465	103.157	2537.314	950.263	91.806
9	2603.435	949.249	101.844	2603.279	949.121	103.157	2604.948	949.123	92.187
10	2572.076	944.489	134.584	2572.158	944.353	130.836	2573.086	944.050	121.014
12	2540.603	913.976	102.880	2540.683	913.733	103.287	2538.629	912.959	105.816
13	2603.417	910.396	101.240	2604.033	910.282	102.656	2606.305	909.284	105.854
14	2568.218	881.307	122.330	2568.212	880.884	119.489	2568.891	878.834	108.282
18	2512.096	942.226	85.627	2512.272	942.251	85.166	2508.843	941.442	88.947
23	2646.820	942.718	27.912	2648.852	942.281	32.921	2652.165	942.159	35.919
24	2630.615	937.758	80.538	2631.061	937.660	81.476	2634.178	936.910	85.173

Table 2 3D coordinates of selected real-life natural features (test points) on the real-life human face

ID	X (Bundle) (mm)	Y (Bundle) (mm)	Z (Bundle) (mm)	X (Natural Features) (mm)	Y (Natural Features) (mm)	Z (Natural Features) (mm)	X (Control Frame) (mm)	Y (Control Frame) (mm)	Z (Control Frame) (mm)
1	2491.338	985.000	68.934	2491.755	985.135	68.794	2488.813	986.321	71.296
2	2523.993	1036.449	81.698	2524.068	1036.515	81.599	2520.641	1038.033	85.376
3	2569.566	1055.997	74.400	2569.694	1055.676	73.087	2569.869	1058.454	77.566
4	2610.507	1035.326	72.033	2609.074	1035.639	70.720	2610.867	1037.476	76.875
5	2636.100	981.551	58.166	2635.786	981.735	57.624	2641.375	981.870	63.259
6	2569.086	1009.795	98.967	2569.953	1010.796	94.976	2569.524	1012.802	99.670
7	2475.156	955.252	18.122	2472.732	954.173	22.391	2470.977	955.396	24.138
8	2526.461	962.162	100.254	2527.415	962.683	99.720	2524.307	963.469	102.862
10	2615.344	957.940	88.684	2615.75	957.788	87.994	2616.109	959.815	92.623
11	2645.743	953.631	2.235	2650.282	952.223	7.846	2653.849	953.441	12.415
12	2486.826	931.620	68.577	2487.030	931.462	68.650	2485.364	931.396	69.539
13	2572.501	956.154	128.982	2574.136	957.719	121.651	2573.149	958.973	125.210
14	2641.595	927.743	48.919	2642.165	927.169	49.094	2646.062	927.463	53.222
16	2520.099	911.163	99.649	2520.092	911.125	97.617	2519.689	912.138	99.452
17	2611.781	908.147	89.846	2612.145	907.762	89.663	2612.513	909.143	93.520

ANALYSIS

The preliminary analysis involved the linear distances between the set of the test points on the mannequin and real-life human face. In this analysis, the linear distances gained from bundle adjustment method was used as a *reference* to verify the accuracy of the natural features technique, control frame technique and caliper technique. Advanced analysis involved the study of the depth factor in the stereophotogrammetric measurements by control frame and natural point techniques. The linear distances analysis on the mannequin involved with 10 distances with 15 test points, while the test on real-life human face involved with 9 distances with 15 test points. The statistical analysis (mean, variance, standard deviation and root mean square error) of the differences between all the techniques with the bundle adjustment method was calculated. Table 3 and 4 show the results of the linear distances analysis both on the mannequin and real-life human face, respectively.

Table 3 Linear distances analysis between the test points on the mannequin

From point	To point	Caliper vs. bundle method (mm)	Natural features technique vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	-0.180	0.080	1.720
3	6	-0.350	-0.440	0.260
6	10	-0.210	-1.440	0.500
12	13	0.110	0.500	4.840
1	5	-0.110	0.610	7.660
17	7	-0.200	-0.370	-10.200
9	23	0.150	-2.000	-12.220
4	24	-0.110	0.120	0.900
2	18	-0.170	0.340	2.160
3	14	-0.320	-0.220	3.860
Statistics	*Mean*	-0.139	-0.282	-0.052
	Variance	0.023	0.641	35.909
	Std Dev	0.153	0.801	5.992
	RMSE	**0.207**	**0.849**	**5.992**

Table 4 Linear distances analysis between the test points on the real-life human face

From point	To point	Caliper vs. bundle method (mm)	Natural features technique vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	-0.110	-1.356	3.567
3	6	-0.029	-2.395	-1.606
6	13	-0.562	-2.012	-1.871
16	17	1.595	0.202	0.807
1	5	0.297	-0.698	7.636
7	8	0.664	-1.993	-1.656
10	11	0.627	-4.291	-2.867
4	14	-1.094	1.104	3.557
2	12	0.306	0.147	1.437
Statistics	*Mean*	0.188	-1.254	1.001
	Variance	0.530	2.401	10.494
	Std Dev	0.728	1.549	3.239
	RMSE	**0.752**	**1.994**	**3.391**

The study of the depth factor in the research were being the advance analysis method to prove that the use of natural features technique will enhanced the accuracy of anthropometric landmark measurements via stereo images. The *depth* is defined as the distances between the datum (average distances from camera lens to absolute photogrammetric control points) to the measured anthropometric landmarks along the z-axis. In aerial photogrammetric method, the depth value should not be more than 10% of the flying height in order to gain high accuracy measurements of an actual height of features. The similar formula can be successfully applied in close-range photogrammetry where the depth of all measured points in stereo model will gained higher accuracy in depth if the depth is about $\pm$10% of the object distance. For example, for the object distance of 600mm, the maximum depth value is 60mm. In this research, which involved the comparison of control frame and natural features techniques in the measurement of anthropometric landmarks, the location of the landmarks from the datum is different (Figure 7).

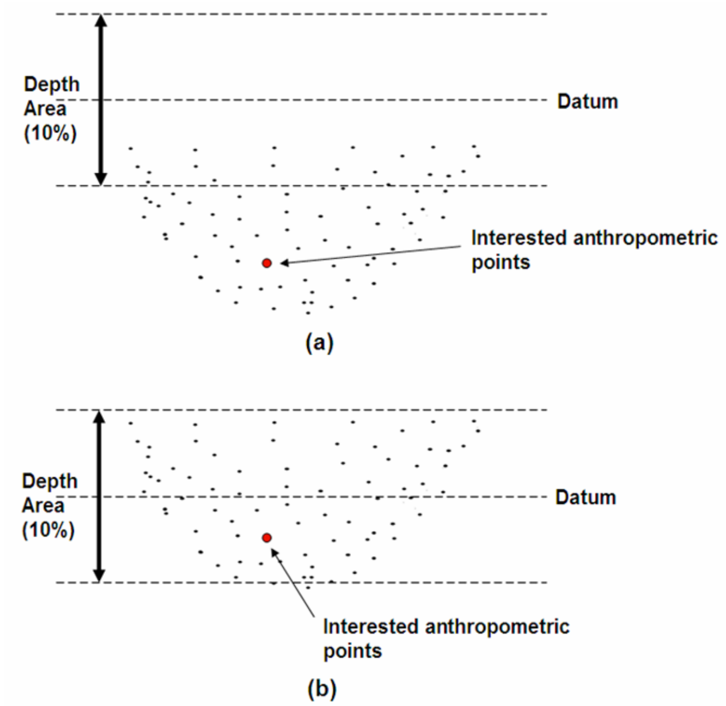

Figure 7 Location of craniofacial landmarks and the photogrammetric measurement datum of (a) control point technique and (b) natural features technique

The statistical analysis involved the two variable regressions between the errors in z coordinates versus the percentage of depth for each test points in both method and the plots of both results are provided (Figure 8 and Figure 9). As general, both plots show the logical results where the increase of depth value (percentage of depth) will increase the error in z coordinates of the anthropometric landmarks. The results also show that the natural features technique is more accurate than the control frame technique. The optimum accuracy for the configuration of the stereo cameras is 0.25mm and the depth percentages of 20% and below was recorded to be true with the accuracy of z coordinate within 0 to 1mm.

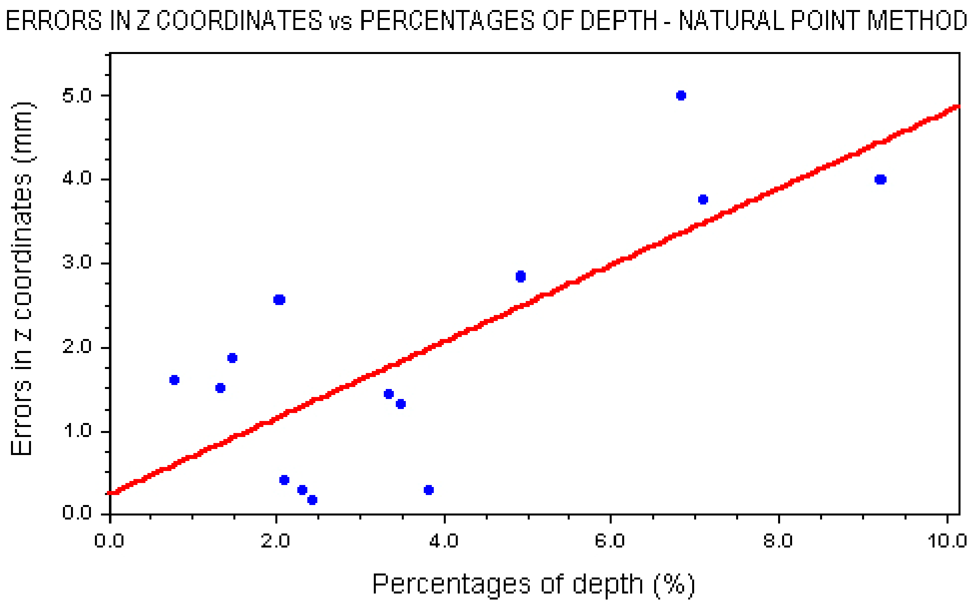

Figure 8 Depth analysis – natural features technique

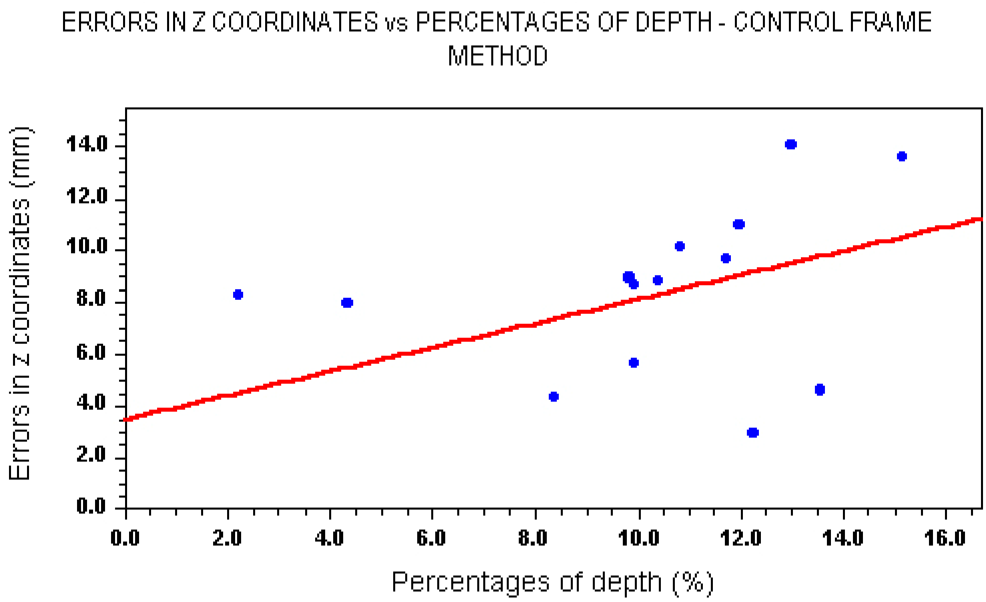

Figure 9 Depth analysis – control frame technique

The *F test statistic* was also used to verify the accuracy of the natural features technique. The test involved the analysis of population variance to test the significance of differences among the two techniques. The null hypothesis H_o (the accuracy of the two methods are the same) was tested against the alternative hypothesis H_A. The F-test for two population variances (variance ratio test) is suitable for testing the hypothesis since the accuracy of both methods is considered into account. The value is computed from the following formula:

$$F = \frac{S_1^2}{S_2^2} \tag{1}$$

Where S_1^2 represent variance of the errors in z coordinates for control frame method and S_2^2 represent variance of the errors in z coordinates for natural point method. The results of the test are provided in Table 5.

The results show that with 12 degree of freedom, the calculated *F* value is 4.492958. The critical value for *F* (from *F*-Table) is 2.686637. With these results, we rejected the null hypothesis and it is statistically proved that the accuracy of the two techniques is not the same. It's also proving that the natural features technique was the accurate method for the measurements of the anthropometric landmarks on the real-life human facial surface.

Table 5 *F variance ratio test* results

Method	*Variance*	*Degree of freedom*	*F value (calculated)*	*Critical F value (Table)*
Control Frame	10.04033	12		
Natural Point	2.234681	12		
			4.492958	2.686637
		Decision	Reject Ho	

FINAL EVALUATION OF PROPOSED TECHNIQUE

For final evaluation of the natural features technique, the technique was tested on the real-life human face without having any signalized targets to represent the natural features. The number of six selected natural features was used as test points and accurately measured by photogrammetric bundle adjustment (Figure 10). The 3D coordinates gained from the bundle adjustment method were selected as reference values. At the same time the similar selected natural features was measured using natural features and control frame techniques (Table 6). The 3D coordinates of both techniques (acquired from stereo measurements) were than compared with the 3D coordinates gained from bundle adjustment. The root mean square error (RMSE) value of the 3D coordinate differences was than calculated (Table 7).

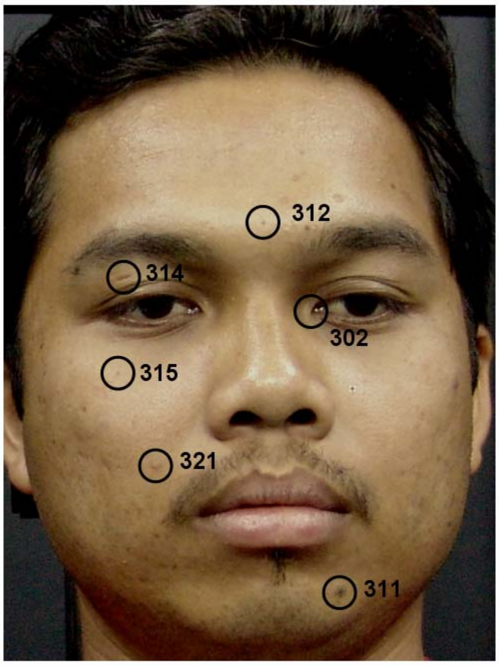

Figure 10 Selected natural features as test points

Table 6 3D coordinates of the selected natural features as test points

ID	X (Bundle) (mm)	Y (Bundle) (mm)	Z (Bundle) (mm)	X (Natural Features) (mm)	Y (Natural Features) (mm)	Z (Natural Features) (mm)	X (Control Frame) (mm)	Y (Control Frame) (mm)	Z (Control Frame) (mm)
302	494.987	441.666	135.194	494.915	441.630	135.041	496.668	441.330	123.338
311	503.696	350.880	142.704	503.782	350.316	143.927	505.572	347.963	130.074
312	477.479	469.187	150.929	478.318	469.434	149.722	478.954	469.753	136.810
314	432.230	452.385	138.444	432.199	452.540	138.132	431.738	452.267	124.461
315	431.687	421.251	139.741	431.735	421.890	140.836	431.837	421.257	124.461
321	442.932	391.326	145.140	442.787	391.572	145.086	443.514	389.738	131.196

Table 7 Results of the test

ID	X (Natural Features-Bundle) (mm)	Y (Natural Features-Bundle) (mm)	Z (Natural Features-Bundle) (mm)	X (Control Frame-Bundle) (mm)	Y (Control Frame-Bundle) (mm)	Z (Control Frame-Bundle) (mm)
302	-0.072	-0.036	-0.153	1.680	-0.336	-11.856
311	0.085	-0.564	1.222	1.875	-2.917	-12.630
312	0.838	0.246	-1.207	1.474	0.565	-14.119
314	-0.031	0.154	-0.312	-0.492	-0.118	-13.983
315	0.047	0.638	1.094	0.149	0.005	-15.280
321	-0.145	0.245	-0.054	0.581	-1.588	-13.944
Mean	0.120	0.113	0.098	0.878	-0.731	-13.635
Std Dev	0.330	0.363	0.838	0.865	1.173	1.105
Variance	0.108	0.132	0.702	0.748	1.377	1.222
RMSE	**0.351**	**0.381**	**0.843**	**1.232**	**1.383**	**13.680**

CONCLUSION

In the paper, the use of stereophotogrammetric method has been discussed for measurements of craniofacial landmarks. The use of natural features technique was statistically approved and found to be an effective method to improve the accuracy of the non-contact craniofacial anthropometric measurements (*mannequin test* - RMSE value of 0.8mm and 6.0mm both for natural features technique and control frame technique, respectively, *real-life human face* – RMSE value of 2.0mm and 3.0mm for natural features technique and control frame technique, respectively). In-term of the accuracy of the 3D coordinates of the craniofacial landmarks (especially for Z coordinate), the RMSE value of 0.8mm was gained by using the natural features technique compared to the control frame technique with the RMSE value of 14.0mm.

By using the natural features technique, there is no need to shorter the camera to object distance and the optimum coverage of the stereo mapping were maintained. The shape and location of the natural points was easily obtained since the setup of the camera system covered the craniofacial measurement area. For high accuracy absolute orientation of the stereo models, the selected natural features need to be well distributed in the overlapping area. The number of six natural features was needed for optimum accuracy of absolute orientation.

In the research, the proposed method need medium extra time to proceed since the additional time was needed to obtain the 3D coordinates of the selected natural features. The Australis camera calibration was used to run the bundle adjustment process for high accuracy 3D coordinates of the natural features. Since the similar software was used for calibrating the stereo cameras and measuring the 3D coordinates of the natural features, there is no additional cost for obtaining the natural features 3D coordinates using other third party software.

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